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Modeling of Non-equilibrium Processes in Oil Trunk Pipeline Using Godunov Type Method

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Abstract

The Article presents the numerical method of solving the system of one-dimensional non-stationary equations describing oil movement in the oil pipeline. The method is aimed at modeling the non-equilibrium and transitional processes in the oil pipelines in the normal and emergency modes. This new developed method can be applied for relaxation non-equilibrium flow case, that can't be modeling using another methods. Also this method is aimed at modeling the non-equilibrium and transitional processes in the liquefied hydrocarbon pipelines in the normal and emergency modes. Phase non-equilibrium flow is considered for boiling liquids transporting pipeline.

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Nomenclature

ρ, p, u averaged over the pipeline cross section density, pressure and oil velocity sound velocity

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c_0, ν	oil sound velocity and oil viscosity
d, k	pipeline diameter and internal surface roughness
g	acceleration of gravity
P_0	outer pressure
S_0, l_0	area and distance of hole
t	time
U_0	outflow velocity
x	distance from the beginning of the pipeline
α	discharge coefficient, equals 0.6
β	sinus of the pipeline decline angle
$\Delta x, \Delta t$	space and time steps
$\lambda(\text{Re})$	friction coefficient as function of Reynolds number
ρ_0	initial oil density
Φ_{mi}, Φ_{pi}	mass and pulse fluxes for i -th cell

1. Introduction

While operating liquid transporting pipeline systems, in case of pump stations stop or valves shut down, certain transitive, mechanically non-equilibrium processes, can take place. During these processes pressure waves can develop. Compression waves, spreading along a pipeline, can cause pressure overload and consequently provoke the pipeline burst or dangerous defects appearance. Decompression waves can cause critical pressure drop, able to spoil the flow continuity, and that, in turn, will provoke a number of negative processes, like shock waves amplification or system elements vibration increase [1, 2].

Thus, a hydraulic shock has contributed to the pipeline burst at Sheskhari oil terminal (Novorosiysk) [3].

The current Russian technical standards of oil and petroleum pipelines layout do not contain any complete methodologies, recommendations, rules or requirements on design conceptions, aimed at mechanical safety (strength) of a pipeline system under transitive mechanically non-equilibrium processes. So the problem is really actual and the given research proposes using the unified approach of numerical modeling not only for a pipeline strength calculation, but for industrial safety and risk assessment as well..

Lots of studies are dedicated to modeling pipeline flow. While modeling pipeline flows, method of characteristics (MC) is commonly used. [1] This method is based on the assumption, that disturbances velocity is constant. As soon as this velocity isn't constant, using MC becomes difficult. There are works using finite-difference methods for calculating pipeline flows [4]. These methods are more universal compared to MC. However, their difficulty is that not all the properties of initial differential equations remain in finite differences. Therefore specific methods are needed to provide the good coincidence of numerical and analytical solutions.

Godunov type method is more universal compared to specifications method [5].

This work presents the model and the numerical method of calculating mass, pulse, energy conservation equation within Godunov's approach, to predict the operation of a sophisticated pipeline system in various modes.

2. Statement of the problem

The following incident scenario is considered.

At a trunk pipeline at a time moment t_0 and at distance l_0 , a hole with S_0 square is produced. That will cause oil release, pressure drop at the release point and rarefaction waves spread. The rarefaction waves reduce the pressure along the line and having reached the start of it, they cause the pressure drop at the exit of the pump. That in turn causes either the pump stop or its operation change. Before that moment the mode of stationary flow can install.

If the pumps in the beginning and at the end of a pipeline start stopping, from the beginning of the pipeline rarefaction wave will spread and from the end compression one will spread. The oil flow was stopped by these waves.

Then they shut the valves at the trunk pipeline. After waves circulation a pressure profile evolves into state according to elevation and release rate. Oil flow stops after complete oil release.

3. Conservation equations

When the temperature is constant the following equation are used to describe non-stationary one dimensional oil flow in pipeline:

continuity equation

$$\frac{\partial \rho}{\partial t} = -\frac{\partial(\rho u)}{\partial x}, \quad (1)$$

pulse conservation equation

$$\frac{\partial(\rho u)}{\partial t} = -\frac{\partial(\rho u^2)}{\partial x} - \frac{\partial p}{\partial x} - \lambda(\text{Re}) \cdot \frac{|u|u\rho}{2d} - \rho g \beta, \quad (2)$$

pressure as density function (equation of state)

$$p - p_0 = c^2(\rho - \rho_0). \quad (3)$$

Initial and boundary conditions are necessary to close equations (1)-(3). To determ $\lambda(\text{Re})$ the Colbrooke-White correlation was used:

The outflow velocity U_0 at release point was calculated using Bernulli formula:

$$U_0 = \sqrt{2(p - P_0)/\rho}. \quad (4)$$

4. Conservation equations

Equations (1)–(5) were solved numerically using original Godunov's method [5]. Godunov's method bases on calculations of the mass, pulse and energy fluxes for each elementary cell. These fluxes are calculated for each cell side. Summing for some time interval all fluxes for some cell one can calculate change in mass, pulse and energy for this cell. Then one can calculate the new values of density, velocity and energy for the cell. The numerical solution includes three stages.

Stage I. Equations (1)-(3) were solved without friction and gravity. At this stage mass (Φ_{mi}) and pulse (Φ_{pi}) fluxes were calculated for each i -th cell. To find mass and pulse fluxes we use solution of Reiman problem. Acoustic Reiman solver was used, because oil is weakly compressible media. Then new values of ρ_i^{n+1} density, p_i^{n+1} pressure and u_i^{n+1} velocity can be defined for i -th cell:

$$\rho_i^{n+1} = m_i^{n+1}/\Delta x = (m_i^n + \Phi_{mi} \cdot \Delta t)/\Delta x, \quad u_i^{n+1} = R_i^{n+1}/m_i^{n+1} = (R_i^n + \Phi_{pi} \cdot \Delta t)/m_i^{n+1}. \quad (5)$$

Pressure in i -th cell at $n + 1$ time step is calculated using equation (3).

Stage II. At this stage friction and gravity are taken into account. Velocity in i -th cell is calculated as following:

$$u_i^{n+1} = u_i^{n+1} - \lambda(\text{Re}_i^{n+1}) \cdot |u_i^{n+1}| u_i^{n+1} / (2d) \cdot \Delta t - g \beta \cdot \Delta t \quad (6)$$

Stage III. The oil release through hole are introduced at third stage. Mass of oil released through hole is taken away from i -th cell. This mass is calculated using following equation:

$$\Delta M = \alpha S_0 \rho_i U_0 \Delta t. \quad (7)$$

5. Test calculation of mechanically non-equilibrium flow

The numerical modeling of oil release were performed using developed approach. The pipeline length was equal 100 km, $d=500$ mm, $k=100$ μm . Oil was injected into the pipeline by pump. The pipeline elevation increases from 0 m in the beginning of pipeline to 100 m at the middle of pipeline (50 km), then elevation decrease to 0 m at the end

of pipeline. There are two valves at the pipeline, one is placed in the beginning of the pipeline, and the second valve is placed at the end of pipeline. Pressure at the end of pipeline is equal 1,3 MPa. We consider the following scenario of incident: the pump starts at $t=0$ s and both valves are open; the hole ($S_0=9,81 \cdot 10^{-3} \text{ m}^2$) forms at the highest point ($l_0=50$ km) at 600 s; at 1200 s pump stops and valves shut down. The oil has following properties: $\nu=1 \cdot 10^{-5} \text{ m}^2/\text{s}$; $c_0=1300 \text{ m/s}$, $\rho_0=860 \text{ kg/m}^3$.

Pressure profiles are presented in Fig. 1 (a) for following time moments: 580 s (20 s before rupture), 620 s (20 s after rupture), 1180 s (20 s before valve shutdown), 1220 s (20 s after valve shutdown), 1800 and 3600 s. Profiles at 580 s correspond to steady state flow with oil velocity 1.3 m/s.

Two rarefaction waves propagate from the rupture point. It is well seen in Fig. 1 (a) for 620 s. After the rupture the oil flow evolves into new steady state flow. This flow is shown in Fig. 1(a), $t=1180$ s. Two waves are generated, when valves are shut down. Rarefaction wave is generated in the beginning of the pipeline, and compressive wave is generated at the end. These waves are shown in Fig. 1(a), see curves for $t=1220$ s.

After the valves were shut down and pressure relieved, flow stopped, and pressure distribution evolved into hydrostatic profile (see Fig. 1 (a), $t=3600$ s).

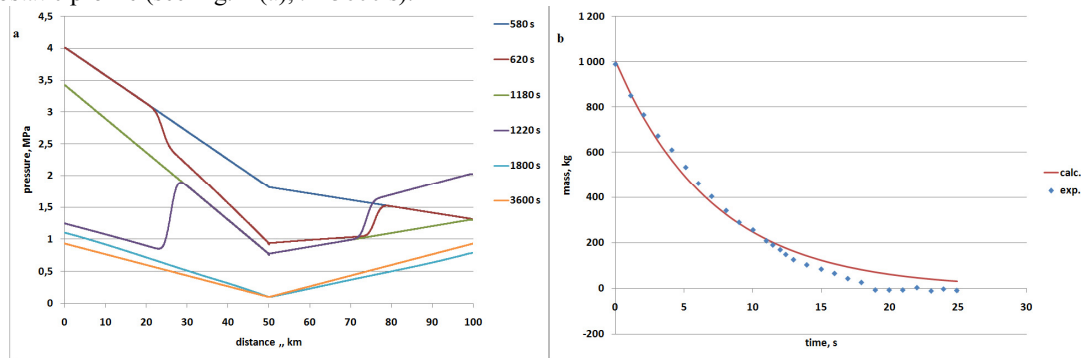


Fig. 1. Test calculations: (a) pressure vs. distance at different time points: 1 — 580 s; 2 — 620 s; 3 — 1180 s; 4 — 1220 s; 5 — 1800 s; 6 — 3600 s; (b) mass content of the 100 m long pipe.

6. Test calculation of phase non-equilibrium flow

It should be noted that above we considered isothermic slightly compressible flow. But Godunov type method can be generalized for non-equilibrium multiphase flow (boiling liquids). The results of numerical calculation for propane release from 100 m long tube are presented in Fig.1 (b). We consider a full bore rupture at the end of a pipe. As one can see there is a good coincidence between calculated and measured [6] values of mass

Conclusion

So the new approach is developed to model non-stationary pipeline flows. This approach is based on numerical solution equations (1)-(5). This approach uses Godunov type numerical method. Proposed approach take into account real pipeline characteristics: including elevation, presence of pumps, valves, relief valves, loopings and others.

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